# Study for relation between direction of relativistic jet and optical polarization angle with multi-wavelength observation

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Blazars are thought to possess a relativistic jet that is pointing toward the direction of the Earth and the elect of relativistic beaming enhances its apparent brightness. They radiate in all wavebands from the radio to the gamma-ray bands via the synchrotron and the inverse Compton scattering process. Numerous observations are performed but the mechanism of variability, creation and composition of jets are still controversial.
We performed multi-wavelength monitoring with optical polarization for 3C 66A, Mrk 421, CTA 102 and PMN J0948+0022 to investigate the mechanisms of variability and research the emission region in the relativistic jets. Consequently, an emergence of new emission component in flaring state is suggested in each object. The most significant aspect of these results is its wide range of sizes of emission regions from $10^{14} - 10^{16}$ cm, which implies the model with a number of independent emission regions with variety sizes and randomly orientation. The "shock-in-jet" scenario can explain high PD and direction of PA in each objects. It might reflect the common mechanism of flares in the relativistic jets.

## 1. INTRODUCTION

Blazars are highly variable active galactic nuclei (AGN) which emit radiation at all wavelengths from radio to gamma-rays. They have strong relativistic jets aligned with the observer's line of sight and are apparently bright due to relativistic beaming. Outstanding characteristics of blazars are their rapid and high-amplitude intensity variations or flares. Blazar consists of several sub-classes. BL Lac objects are detected to have weak emission line of equivalent width $< 5$ Å in the observer's optical band definition. In contrast, flat spectrum radio quasars (FSRQs) shows relatively strong emission lines. Blazars also can be classified into three types, based on their peak frequency of synchrotron radiation $\nu^S_{\rm peak}$ [3]; low-synchrotron-peaked blazars (LSP; for sources with $\nu^S_{\rm peak} < 10^{14}$ Hz), intermediate-synchrotron-peaked blazars (ISP; for $10^{14}$ Hz $< \nu^S_{\rm peak} < 10^{15}$ Hz) and high-synchrotron-peaked blazars (HSP; for $10^{15}$ Hz $< \nu^S_{\rm peak}$). Due to relativistic effect, radiation from jets dominates the overall spectral energy distribution and hence, their spectra in the optical band are featureless compared with other AGNs. From this reason, blazar is one of most suitable objects to study the jets.

Polarized radiation from blazars is one of the evidence of synchrotron radiation in low energies and it also varies drastically. The polarization of blazars is of interest for understanding the origin, confinement, and propagation of jets [4, 21]. Mead et al. (1990)[18] performed a large-sample study of blazars in the optical band and showed that high polarization degree (PD) and variability of polarization are common phenomena in blazars. Ikejiri et al. (2011)[10] reported statistical photopolarimetric observations of blazars with a daily timescale, and suggested that lower luminosity and higher peak frequency of synchrotron radiation objects (such as HSP blazar) had smaller amplitudes in their variations both in the flux, color, and PD. The author also reported the about 30% of blazars showed correlation between the optical flux and PD. Numerous observations are performed but the mechanism of variability, creation and composition of jets are still controversial.

In efforts to find a common mechanism of jets, we performed observations on various types of AGNs. Simultaneous multi-wavelength and optical polarimetric observations are powerful tools to probe the emission region in jets, thus we performed wide-band multi-wavelength (from radio to TeV gamma-ray) observations of relativistic jets in several types of AGNs with various timescales (from minute to year) to study of structures and emission regions of relativistic jets.

## 2. Observations

We constructed the framework of multi-wavelength and optical polarimetric observations of relativistic jets in AGNs with the *Fermi* Gamma-ray Space Telescope, Monitor of All-sky X-ray Image [MAXI; 17], the *Swift* Gamma-Ray-Burst Explorer [8], the Kanata optical and near infrared telescope, Optical and Infrared Synergetic Telescopes for Education and Research (*OISTER*), and Mizusawa VLBI Observatory.

We performed four objects observation with optical flux and polarization to see the relations between polarization angle (PA) and the direction of radio jets in the flaring state. In efforts to find a common mechanism of jets, we selected the different types of AGNs

to see the difference between them. This study focused on four AGNs; ISP blazar 3C 66A, HSP blazar Mrk 421, FSRQ CTA 102 and radio-loud narrow-line Seyfert 1 galaxy (RL-NLSy1) PMN J0948+0022. Note that RL-NLSy1 is not the class of blazar but it thought to possess relativistic jet [2]. Some radio galaxies also known as GeV gamma-ray emitter and those class of AGNs might play an important role to probe the emission region in the relativistic jets (e.g., [20]). Individual results are reported in Itoh et al. (2013a)[12], Itoh et al. (2015, submitted to the PASJ)[15], Itoh et al. (2013b)[13] and Itoh et al. (2013c)[14] respectively. We selected the flare with good correlation between polarized flux and total flux in optical band.

## 3. Summary of case studies

In this section, we summarize our studies of individual blazar, Temporal variability in optical flux, polarization flux and PA are shown in figure 1. Table I shows a summary of differential angle ($\Delta$DA) between position angle of radio jet measured by VLBI or VLBA ([5], [19], [7] and [6])

### *A. 3C 66A*

We studied the long-term variations of 3C 66A over 2 years in the GeV band with *Fermi* and in the optical (flux and polarization) and near infrared band with the Kanata telescope. In 2008, we find a correlation between the gamma-ray flux and the optical properties. This is in contrast to the later behaviours during 2009–2010, a weak correlation along with a gradual increase of the optical flux. We conclude that the different behaviors observed between the first year and the later years might be explained by postulating two different emission components. $\Delta$DA shown in Table I indicates that the position angle of radio jet is close to the average PA. It should be noted that a correlation between PD and total flux is significant in 2009.

### *B. Mrk 421*

We observed the long-term variability of Mrk 421 from optical to X-ray band using the *Swift*, MAXI, and Kanata telescope from 2010 to 2011. In 2010, the variability in the X-ray band is clearly large, while the optical and UV flux shows gradual decreasing. Polarization properties also show the unique variability in 2010. The variation on the Stokes parameter QU plane suggested the presence of the proper polarization. On the other hand, the variability in the X-ray band is small in 2011, although the variability in the optical and UV band is relativistically large compared with that in 2010. We speculated that Mrk 421 has different variability mechanisms between 2010 and 2011 and emergence of a new emission component which have systematic difference of polarization at different periods. $\Delta$DA indicates that PA is aligned to the parsec scale jet in 2010. We also found a good correlation between optical flux and polarized flux in 2010. These behaviours are similar to that in 3C 66A.

### *C. CTA 102*

We densely monitored CTA 102 in the optical and near-infrared bands for the subsequent ten nights using *OISTER*, following *Fermi*-LAT detection of the enhanced gamma-ray activity. On MJD 56197 (2012 September 27, 4-5 days after the peak of bright gamma-ray flare), a polarized flux showed a transient increase, while a total flux and PA remained almost constant during the "orphan polarized-flux flare". We also detected an intra-night and prominent flare on MJD 56202. Emergence of a new emission component with high PD up to 40% would be responsible for the observed two flares, and such a high PD indicates a presence of highly ordered magnetic field at the emission site. The observed directions of PA is perpendicular to the jet. The total and polarized fluxes showed quite similar temporal variations, but PA again remained constant during the flare.

### *D. PMN J0948+0022*

We performed optical photopolarimetric monitoring of the RL-NLSy1 galaxy PMN J0948+0022 on 2012 December to 2013 February triggered by the flux enhancement in near infrared and $\gamma$-ray bands. Thanks to one-shot polarimetry of the HOWPol installed to the Kanata telescope, we have detected very rapid variability in the polarized-flux light curve on MJD 56281 (2012 December 20). The rise and decay times were about 140 sec and 180 sec, respectively. The PD reached $36 \pm 3\%$ at the peak of the short-duration pulse, while PA remained almost constant. The high PD provides a clear evidence of synchrotron emission within a highly ordered magnetic field at the emission site. These results provide new observational evidence that highly ordered magnetic field is present inside a very compact emission region of the order of $\sim 10^{14}$ cm and imposes severe constraint on theoretical studies unless central black hole mass is much smaller than currently considered. we found that PA in MJD 56202 is aligned to the parsec scale jet. Temporal profiles of the total flux and PD showed highly variable but well correlated behavior and discrete correlation function analysis revealed that no significant time lag of more than 10 min was present.

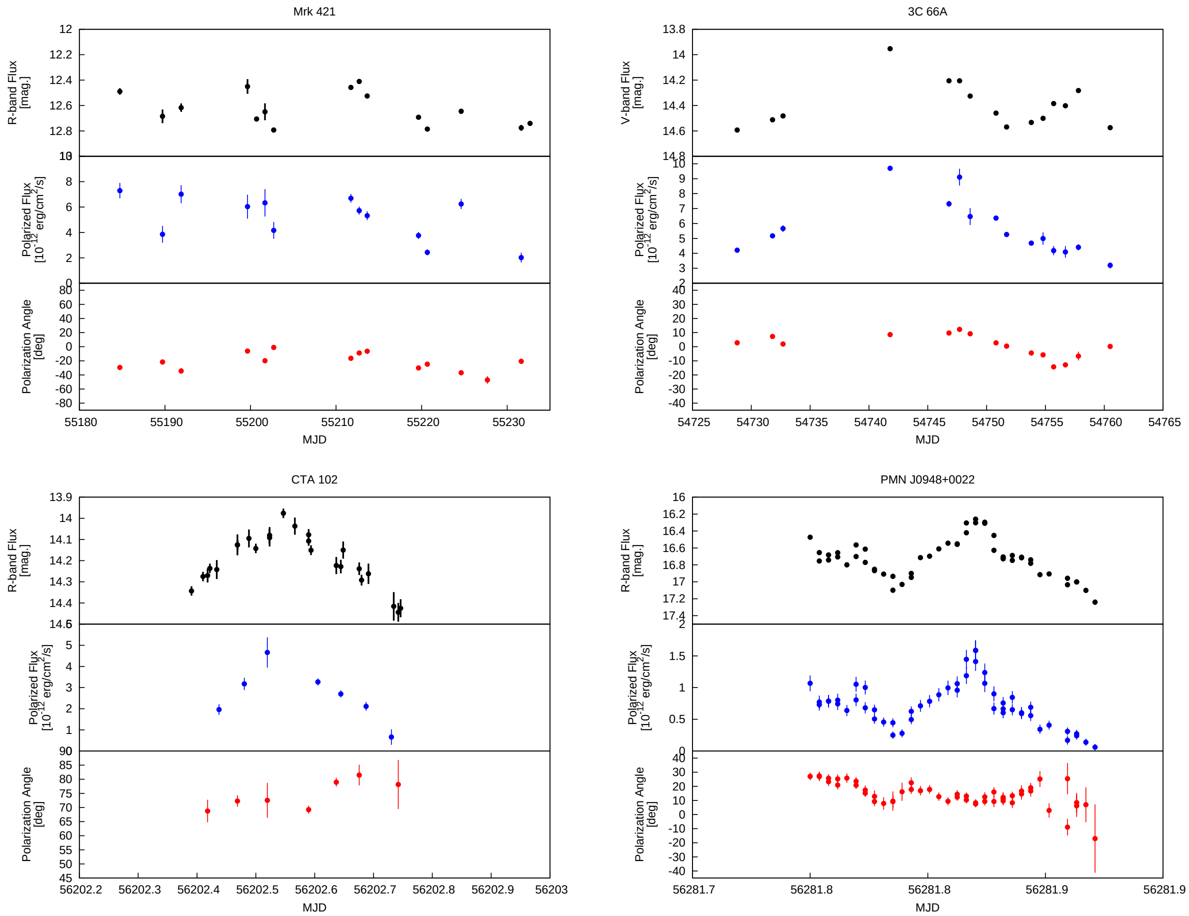


Figure 1: Light curves for each source. From top to bottom, the histories of the total flux in the $R_C$ band, the polarized flux, and the polarization angle (PA) are shown. Note that the time scale of CTA 102 and PMN J0948+0022 (bottom two sources) are different from that in 3C 66A and Mrk 421. Details of each light curve are reported in [12], [13], [14] and [15]

Table I Summary of differential angle for each object.

| **Object name** | **AGN type** | $\Delta DA^1$ [deg] |
|---|---|---|
| 3C 66A | BL Lac (ISP) | $0 \pm 5$ |
| Mrk 421 | BL Lac (HSP) | $10 \pm 10$ |
| CTA 102 | FSRQ | $80 \pm 10$ |
| PMN J0948+0022 | RL-NLSy1 | $5 \pm 5$ |

[1]: Differential angle between the position angle of radio jet and optical polarization angle.

## 4. Discussion

A common characteristic among BL lac objects and RL-NLSy1 is that PA aligned with a direction parallel to the jet (see TableI). This phenomenon is well explained with the framework of "shock-in-jet" scenario, in which high PD and direction of PA are well explained with compressed emission region by the internal shocks. This phenomena is explained with below mechanism; a compressed shock that is perpendicular to the jet flow results that the electric polarization vector to be perpendicular to the emission blob and aligned with the jet axis. Impey et al. (2011)[11] reported that about 60% quasars shows alignment of the position angle of jet and polarization angle. Especially, author found that in 10 out of 11 BL Lac objects shows good alignment. It should be noted that these measurements of PA were collected without considering the flux state. Similar tendencies in hourly-scale variability were reported in other BL Lac objects [e.g., AO 0235+164, 9]. On the other hand, CTA 102 which is classified as FSRQ shows a different tendency. The difference of relation between PA and direction of the jet might be reflecting a difference of jets between BL lac objects and FSRQs. In general, FSRQs thought to have weaker shocks and/or a stronger underlying magnetic fields such as large-scale helical magnetic fields. Given this complicated situation, the measured PAs significantly different from the

jet direction can still be accounted for by the "shock-in-jet" scenario. Therefore, it is suggested that the "shock-in-jet" is a common phenomena in relativistic jets, which independent on the synchrotron peaks, types of AGNs and timescale. Similar relations between PA and direction of the radio jet are reported in measurements of radio polarization [16]. It might reflect the common mechanism of flares in the relativistic jets but we need more sample to confirm this trend.

## 5. Acknowledgments

This work is supported by Optical & Near-infrared Astronomy Inter-University Cooperation Program and Grants-in-Aid for Scientific Research (23340048, 24000004, 24244014, and 24840031) by the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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